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August 28, 2014

Journal of Physics: Conference Series

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Hyperfine splitting of the $2s_{1/2}$ and $2p_{1/2}$ levels in lithiumlike Pr^{56+}

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Abstract.

Measurements of hyperfine splittings in highly charged ions are sensitive to nuclear structure and field distribution details, if the atomic structure is understood in sufficient detail. We discuss the reasoning behind various recent experiments and what advantage is offered by the study of the Li-like ion of a mid- Z element such as praseodymium.

1. Introduction

The hyperfine splitting of spectral lines has been recognized in the 1930s as a window for the study of nuclear properties, and a large number of nuclear spins have been determined mostly from highly resolved optical spectra. Systematic studies of isotopes and isobars were helped by laser spectroscopy since the 1970s and have yielded hyperfine constants of many nuclei which were tried to interpret by models of nuclear shape and magnetization. A key problem in the quest for determining the nuclear properties, however, was the fact that the actual observations were performed on multi-electron atoms. This problem is aggravated by the Z^3 dependence of hyperfine splittings on the atomic number (nuclear charge) Z , which calls for high- Z elements in the most sensitive measurements of hyperfine splittings. High- Z elements imply relativistic effects in the electronic shells and notably large quantum electrodynamic (QED) contributions from the strong Coulomb field the electrons experience near the nucleus, where they sense the nuclear magnetic field distribution, in addition to the mounting problems of describing such a multi-electron system *per se*.

Theory and atomic structure computations have made great strides to cope with such a complex problem, but it seems advantageous to develop experimental techniques that significantly reduce the complexity by massively reducing the number of electrons involved. The ultimate system here is a hydrogen-like heavy ion, that is a high- Z nucleus with a single electron. The hyperfine splitting in the ground state ($n=1$) of such atomic systems has been studied by optical spectroscopy at the Livermore SuperEBIT [1, 2, 3, 4, 5, 6, 7] and by laser spectroscopy at the Darmstadt heavy-ion storage ring ESR [8, 9, 10]. In various aspects the agreement with theory has not been fully convincing [11]. Of course, theory can be adjusted to match experimental findings, but then theories that seem to do well for $n=1$ levels may be tested

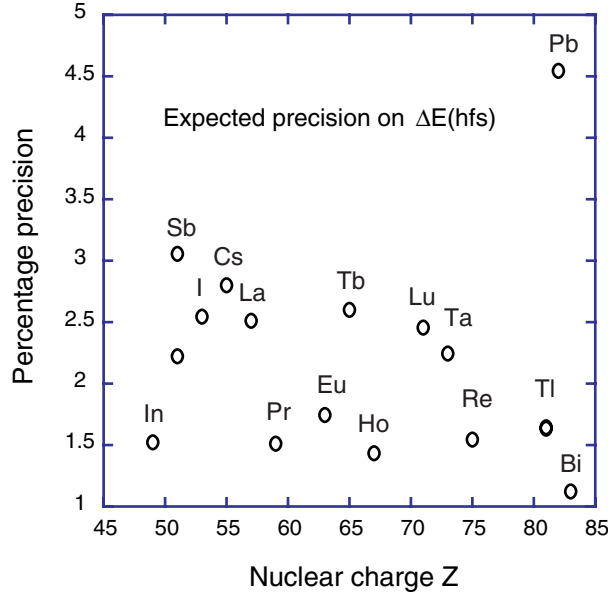


Figure 1. Expected precision of determining the hyperfine splittings in EUV observations of few-electron ions with a flat-field grating EUV spectrometer [12] at Livermore. Similar distributions apply to other instruments, because the relation of the hyperfine splitting to the overall transition energy matters. Incidentally, isotopes of Bi, Pb, Tl, Re, Ho, and now Pr, have been measured by various techniques, and In and Eu are likely candidates for future work.

by measurements of the $n=2$ hyperfine structure. High-resolution observations of transitions in the $n=2$ shell of H-like ions suffer from the short level lifetimes involved which leads to lifetime broadening of the spectral lines. This effect can be largely avoided by blocking any decays to the $n=1$ shell; in Li-like ions the ground state is a $n=2$ level, at the cost of theory having to deal with a three-electron system (which is much simpler though than, say, a 79-electron system in the case of Pb), with the added benefit of a much higher production yield of the Li-like atomic species (compared to H-like ions) in the experiment.

2. Choice of Li-like ions

S electrons are the best probes of the nuclear structure, because their wave function does not vanish at $r=0$. In Li-like ions, the transitions with the largest contribution from hyperfine structure are the $2s$ - $2p$ transitions. The fine structure intervals (such as $2p_{1/2} - 2p_{3/2}$) increase with Z^4 ; in high- Z elements, the $2s$ - $2p_{1/2}$ transitions lie in the extreme ultraviolet (EUV), while the $2s$ - $2p_{3/2}$ transitions fall into the X-ray range. The sensitivity of the transition energy measurement to hyperfine effects thus is much larger for the former. The sensitivity is much higher again for observations of the transition between the hyperfine levels of the $2s_{1/2}$ level, but these transitions are in the infrared where the search for such a resonance in a laser experiment suffers directly from the uncertainty of theoretical predictions. It is for this reason that the laser experiment at GSI Darmstadt [10] has taken many years and several attempts to find a resonance in Bi^{80+} , even after X-ray and EUV observations at Livermore [5, 6] had narrowed the parameter space.

In general, one can estimate the sensitivity of any such experiments by the ratio of the hyperfine splitting to the observable transition energy of, for example, observations of the $2s$ - $2p_{1/2}$ transitions in Li-like ions. The hyperfine splitting depends on the nuclear spin and thus on

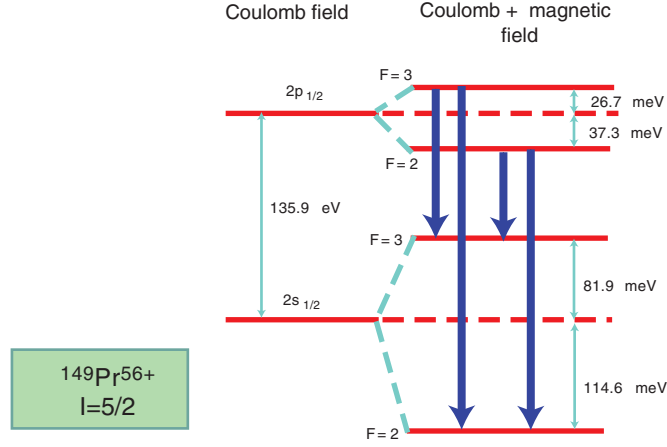


Figure 2. Calculated $2s_{1/2}$ and $2p_{1/2}$ level structure and $2s$ - $2p$ transitions of $^{141}_{59}\text{Pr}$ with the fine structure transition on the left and with the hyperfine intervals indicated on the right.

the nuclear properties of each isotope (and calculated data are available for a number of these), while the $2s$ - $2p_{1/2}$ transition energies usually are calculated without taking nuclear properties into account. For a number of isotopes and $2s$ - $2p_{1/2}$ transitions in Li-like ions such estimates are shown in fig. 1. Similar estimates pertain to hyperfine effects on transitions in the $n=1$ shell, the hyperfine splitting of the electronic levels falling off roughly as n^{-3} .

QED contributions scale approximately with Z^4 , quite similarly to the fine structure splitting and not very much differently from hyperfine effects. QED effects depend on nuclear size and shape. The doubly magic nucleus $^{208}_{82}\text{Pb}$ is very close to spherical and assumed to be well known in radius, whereas until recently the shape of the $^{238}_{92}\text{U}$ nucleus was considered to cause a notable uncertainty in the QED calculations. (Such models and the confidence on their validity are, of course, time dependent.) Hence QED effects are larger in uranium, but possibly under better control in lead. Similar considerations about the nuclear magnetization distribution have lead Shabaev, Volotka and coworkers [13, 14] to suggest that one should measure hyperfine splittings in H- and Li-like ions (and possibly B-like ions as well); some of the less certain terms in the nuclear structure calculations are expected to (largely) cancel in the comparison. Another consideration is that of the relative magnitude of QED effects and hyperfine structure. In the middle of the periodic table (mid- Z elements) the QED contributions are assumed to be small enough and well enough known, so that their uncertainty should be smaller than that of the hyperfine structure.

3. Measurement of Li-like Pr^{56+}

Following the above discussion, we have chosen the isotope $^{141}_{59}\text{Pr}$ (nuclear spin $I=5/2$) for studies of the hyperfine effects in Li- and Be-like ions [7]. This isotope has closed neutron shells but an open proton shell that challenges nuclear theory way beyond the ‘single particle outside of a closed shell’ model, and which results in an above-average hyperfine splitting conducive of reaching a high measurement sensitivity. The calculated $2s$ - $2p_{1/2}$ level structure and transition array is depicted in fig. 2. A sample of our SuperEBIT measurements in the EUV, using our high-resolution flat-field EUV spectrograph and a cryogenically cooled CCD camera, is shown in fig. 3, representing the sum of more individual exposures than displayed in [7], where the technical details of our experiment have been described.

The results of our measurements on the isotope $^{141}_{59}\text{Pr}$, such as the 196.5 ± 1.2 meV $2s_{1/2}$ splitting, agree with theory within the mutual error bars. This indicates a high level of

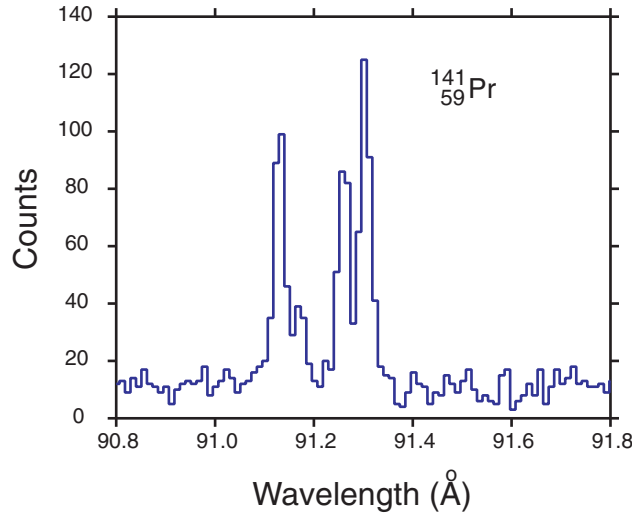


Figure 3. Spectrum of the $2s_{1/2} - 2p_{1/2}$ transition array observed with the isotope $^{141}_{59}\text{Pr}$ in the Livermore SuperEBIT. Several individual spectra have been individually calibrated and then summed.

understanding reached for the atomic structure, which should carry over to higher- Z systems in which relativistic, QED, and nuclear magnetization contributions play a much larger role.

4. Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. E.T. acknowledges support by the German Research Association (DFG) (grants Tr171/18 and Tr171/19).

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